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Engineering Factors for Biomass Baler Design

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Abstract. *Woody biomass is a core element of our nation's strategy to replace imported oil and natural gas with renewable resources. The challenge facing potential biomass users, however, is how to economically recover and transport the material from residential neighborhoods, urban centers and suburban landscapes to distant users. Our preferred solution is to bale the bulky biomass at the roadside to reduce the cost of at-site processing, increase payloads during hauling, and preserve physical properties for more appropriate feedstock processing by woody biomass users. A preliminary step towards this goal is determining the appropriate bale and baler size.*

We have deduced an appropriate target bale size and density for a baler intended to operate in the wildland urban intermix zone as part of forest health and fuels reduction projects. By using a bale size of 1.22 m x 0.79 m x 1.58 m with a green density of 373 Kg/m^3 and an equilibrium density of 250 Kg/m^3 we can maximize truck load potential while minimizing input energy. Furthermore, maximizing truck load potential increases the utilization opportunities for the biomass from residential scale fuel reduction projects by reducing the cost of material transportation.

Keywords. Biomass, Biomass Transportation, Biomass Handling, Biomass Baler

Introduction

Woody biomass is a core element of our nation's strategy to replace imported oil and natural gas with renewable resources. Moreover, the Western Governors' Association's January 2006 task force report concludes that a significant portion of the woody biomass available for power generation in the West must come from fuels reduction projects.

In addition to providing feedstock for power generation / cogeneration facilities, low grade logs and wood strands are the primary raw materials for composite lumber and engineered panel products. The demand for the lowest grade of random veneer has doubled in the past year, mostly due to increased demand from panel and laminated veneer lumber producers.

The challenge facing potential users who gaze longingly at urban biomass sources is how to economically recover and transport the material from residential neighborhoods, urban centers and suburban landscapes to distant users. That is where we at Forest Concepts come in. We are systems, equipment, technology, and business development specialists with the expertise to create a biomass recovery and logistics system that works. Forest Concepts is working under a federal contract from the USDA CSREES SBIR program to develop better methods to collect and transport woody biomass collected from small-scale fuels reduction projects (ranging from residential lots to 20 acre parcels) in the true wildland-urban intermix zone (WUI). Our specific objective is to enable more of the material to be channeled to value-added uses including energy, biorefineries, and engineered wood products.

In 2006 Dr. Dooley, Dr. Fridley, DeTray and Lanning concluded that in the absence of an effective system for collecting woody biomass for value-added uses, project coordinators generally view the materials from small-scale fuels reduction activities as a least-cost disposal problem rather than as an economic opportunity (Dooley et al, 2006). As such, revenue that reduces the cost is welcome, as is a positive story about how the biomass was used to create jobs and economic activity.

The overall system of biomass collection and disposal involves on-site handling, at-site processing, transportation, and at-destination handling/processing. Our objective is not only to reduce the cost of collection and disposal, but also to preserve opportunities for value-added utilization.

Our preferred solution is to bale the bulky biomass at the roadside to reduce the cost of at-site processing, increase payloads during hauling, and preserve physical properties for optimized feedstock processing by woody biomass users.

The Zen of Fuels Reduction

The continuum of forests and natural areas in need of fuels reduction thinning ranges from wilderness and working industrial forests to urban neighborhood greenbelts and overgrown residential lots. Forestlands, greenbelts, and other natural areas are challenging the public with the dual yet interconnected problems of declining forest health and uncontrollable wildfires.

While traditional logging, macerating and thinning is spatially and economically practical in contiguous forests with established forestry infrastructure, conventional logging methods are ill-suited to areas with a patchwork of residential lots, public spaces and forestland / brushland. At the other end of the spectrum are landscape companies, with very high extraction costs per unit of biomass. No less problematic is the fact that the corresponding equipment produces a limited array of end products, namely slash and / or wood chips - neither of which, in most cases, achieves sufficient efficiency to produce material that can be transferred to a commercial use at a cost-neutral or profitable rate. The diagram below – "Zen and the Art of Fuels Reduction" – provides a general overview of the spectrum of fuels reduction and who is carrying out the work at a given scale; community fuels reduction organizations are active across the spectrum, but primarily outside of the commercial lumber sector.

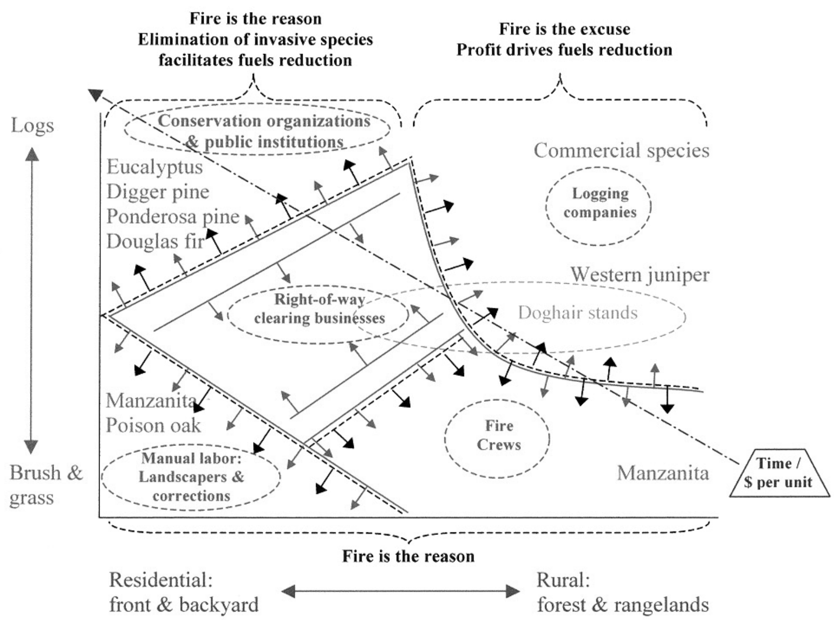

Figure 1. Zen and the Art of Fuels Reduction. This graphic depicts the material characteristics, locations for fuel reduction projects, and entities performing the fuel reduction activies.

The scope of our current research is the material collected from the lower quadrants (from brush and grass through tree limb piece size).

Appreciative Design

The Appreciative Design process (Dooley and Fridley, 1996) was followed to create a baler solution that may be preferred by many of the contractors in the focus areas. Appreciative Design is a structured process to search for a best-set solution to technical and organizational problems. The Appreciative Design process is a significant extension of the hierarchical axiomatic design methodology of Suh (1990; 1995). Suh's axiomatic design was modified through the addition of stakeholder ownership of constraints (McIntyre and Higgins, 1989), and inclusion of many features of the Soft Systems Methodology developed by Checkland (1990).

Baler Design Factors

Stakeholders / Constraint Owners

Stakeholders, or constraint owners, are the individuals or groups that have "influence" over the design of a solution. Stakeholders can range from regulatory agencies to purchasing agents. Table 1 lists stakeholders for the biomass baler project.

Table 1. Stakeholder / Constraint owners for biomass baler project and their respective design influence.

Constraint Owner	Ownership effect
Local and Federal regulatory agencies	Determine roadway transportation laws
Machine operators	Determine how machine is to be used, as well as what types of material baled and in what type of environment
Machine purchasers	Determine cost effectiveness of machine
Residents in fuels reduction areas	Determine environmental impact of machine such as noise and dust levels

Functional Requirements

The overarching functional requirement of this project is to reduce the cost of fuels reduction projects as well as increase value added utilization of biomass material by enabling efficient transportation of biomass material. This statement can be further divided into the following detailed statements:

- Maximize payload on a given transportation network. For this project, we will limit our transportation type to highway vehicles, both commercial flatbed trailers and tractor trailer combinations.
- Maintain piece size as much as practical. This requirement increases value added utilization opportunities further down the supply chain.
- Minimize the use of fossil fuels. As well as the obvious monetary savings, minimizing fuel consumption reduces the environmental impact of the machinery.

Constraints

The following table describes the constraints and design attributes placed on the project by each stakeholder group.

Table 2. Constraints on the biomass baler project, unordered.

Constraint / Design Attribute	Owner
Transportable behind “1 ton” pickup truck	Machine Operator
Capable of working on residential streets without stopping all traffic	Machine Operator
Consume less energy than chipping	Machine Operator
Noise less than that of a chipper	Resident
Fit within a physical dimension that is legal to transport down the public highway system. For this project the baler system can be 2.4 m wide by 4 m tall by less than 10.7 m (8x13x35 ft).	Regulation agency
Allow bale transportation on highway trucks	Machine operator

Allow bale to be moved with a skid steer loader	Machine operator
Produce less dust than a chipper	Resident

Bale Size

As bale size directly dictates many baler mechanical engineering design parameters, we will first determine what the target bale size will be.

Bale size is constrained by multiple characteristics that fall within the constraint bracket of the stakeholders:

- Baler physical dimensions and weight
- Prime handling machinery
- Density
    - Maximize truckload payload
    - Maximize warehouse space
    - Maximize stackability
- Bale physical dimensions to maximize truckload volume
- Input material physical size

Baler Size

We will first examine baler physical dimensions and weight. As noted in the constraints section, the prime mover for this baler will be a 1 ton sized pickup truck. Assuming a 1 ton dually truck with a commercial hitch, the weight of the baler, trailer, and loader arm should be 6,300 Kg (14,000 lb) or less. We know that gooseneck trailers weigh approximately 1,300 Kg (3,000 lb). A grapple loader attachment with outriggers is approximately 900 Kg (2,000 lb). Subtracting our load from our capacity leaves 4,100 Kg (9,000 lb) for the baler itself. Although there are things we can do to save weight in order to get a few more pounds for the baler, this number will serve as a good benchmark.

Balers can be categorized into bale size segments. These segments are shown in Table 3 depicting a prime mover, baler category, estimated maximum productivity, and resulting physical bale size.

Table 3. Baler size category in relation to prime mover, bale volume, and productivity.

Mover	Baler Category	Bales / Hr	Bale Size
Pickup	Extra Small	5	0.028 m^3 (1 ft^3)
1 Ton pickup	Small	50	0.028 – 0.20 m^3 (1 – 7 ft^3)
26000# GVW Truck / 1 Ton + Gooseneck	Medium	5	0.85 – 1.56 m^3 (30 – 55 ft^3)
26000# GVW Truck / 28' tractor trailer	Medium, Auto Tie	10 – 20	0.85 – 1.56 m^3 (30 – 55 ft^3)
48' Tractor trailer	Large	5	1.70 – 3.54 m^3 (60 – 125 ft^3)
Oversize Hauler – 12' x 100,000 lb	Large, Auto Tie	10 – 20	3.54 – 5.66 m^3 (125 – 200 ft^3)
Oversize Hauler – 12' x 100,000 lb	Jumbo	5	6.23 – 15.57 m^3 (220 – 550 ft^3)

We know from the recycling industry that a baler that produces a "medium" bale of roughly 1 cubic meter weighs approximately 3,800 Kg (8,500 lb). Examining Table 3 we see that we can eliminate balers sized at Medium, Auto Tie or larger for this phase of the project.

Density plays a significant factor in the behavior of a bale. Low-density cotton ball type bales do not fully utilize the truck "cube" - the volume available to fill a given shipping device. Extremely high density bales utilize the maximum truck weight capacity, but at the expense of energy needed to create the bales. A third consideration is that denser bales stack better than loosely baled material. If material is to be warehoused or stacked on a lot, poor stackability of a low density bale is a significant safety risk.

We assume baled material will be loaded or reloaded onto a long haul truck for delivery to the closest end user, often a cogeneration power plant or similar facility. Many such power plants are in California. The California Department of Transportation has fairly strict regulations on weight and size limits. We will use an appropriate bale size and density for transportation on a 14.63 m (48 ft) flatbed semi trailer in the state of California as our minimum density (CA DOT, 2006). Truck and trailer hauling is limited either by cubic capacity or payload mass. A 4.27 m (14 ft) maximum load height leaves 2.4 to 2.7 m (8 – 9 ft) of useable cargo space. We will assume 2.4 m (8 ft), ensuring a buffer space. The volume, then, of cargo that can be transported in California (without special permits) is 14.63 m X 2.4 m X 2.4 m, equaling 84.27 cubic meters (3072 cubic feet). A typical payload legal in California is 20,000 Kg to 21,800 Kg (44,000 – 48,000 lb), depending on type of flatbed trailer and truck. We will assume the latter load, supposing a lower capacity trailer could simply take fewer bales. Thus, the lowest density where the maximum legal weight is met before "cubing out" is 250 Kg/m^3 (15.6 lb/ft^3).

Other drivers to increase the bale density must be considered. Increased density improves stack stability. Additionally, there is a cost savings associated with a denser bale - more material packed into a smaller volume requires less wire / twine to bind that material as well as more material being moved (picked up and lifted) per each bale handling event.

Many wildland urban intermix project contractors utilize equipment such as a skid steer loader. A typical skid steer loader, with fork or tine attachments should be able to move and stack the bales produced. A brief survey of local equipment rental shops indicated that 680 Kg (1,500 lb) is a reasonable maximum load for a typical skid steer loader. Thusly, our bale should weigh less than 680 Kg. Using the base line density of 250 Kg/m^3 determined earlier we can calculate that a bale should have a volume no larger than 2.7 cubic meters (96 cubic feet) using the equation 680 Kg / 250 Kg/m^3. This constraint removes large baler and larger options from consideration. Additionally, this constraint is consistent with the prime mover constraint discussed above.

The material being produced at projects sites will also affect the optimal bale size. As stated above, a functional requirement is to maintain piece size as much as practical. Our field characterization of material in 2006 showed that most of the material from the target WUI sites is brush and tree limbs less than 10 cm (4 in) diameter. A 2007 study of material characteristics from WUI type land clearing showed 58% of the pieces are less than 1.2 m (46 in), with overall lengths ranging from 0.3 to 3.2 m (12 – 124 in). Piece diameter ranged from 1.2 to 42.5 cm (0.5 – 16.75 in), with an average diameter of 8 cm (3 in).

From these characterizations it has become obvious that an extra small baler is not appropriate. Clearly much energy would be expended cutting material to size to fit into the bale chamber. From the discussion above, we can conclude that the baler itself should be a “medium” sized baler. This requirement constrains the actual size of the bale to a range of approximately 0.85 – 1.56 m^3 (30 – 55 ft^3).

Bale Density

Target bale density is a key factor in designing a compression system. In order to specify appropriate sized compression mechanisms, we need to know how much force will be required to form an appropriate bale of the appropriate density. We need to understand the life of a bale to specify the correct density. A good bale should hold its form over time and allow stacking of multiple bales (how many depends on the bale size, as “too many” creates an unstable column – an issue not covered in this paper).

Forest Concepts’ experiments with 0.085 cubic meter (three cubic feet) bales of WoodStraw™ mulch have shown that even though a bale is under considerable pressure at the time of baling (enough tension break 250 knot strength poly baling twine consistently at time of knotting) the internal stresses relax quickly to where a minimal 13 – 18 Kg (30 – 40 lb) tension remains in the twine. Bale dimensions, however are stable; the bale does maintain its volumetric footprint while the stresses release. We believe this is do to the nature of both the twine and woody material. In essence the woody material behaves as a visco-elastic material.

Following the visco-elastic material analogy, we can build a logical argument for the appropriate density. The WoodStraw™ material is baled at 240 Kg/m^3 (15 lb/ft^3) and will stack well to 3 meters (9 ft) high independent of other stacks. When multiple stacks are placed together, a second layer can be placed on top. This shows that the bale integrity is maintained, and that the primary stacking issue is column stability, not density. Therefore, a preliminary density target of 250 Kg/m^3 as computed for trucking is acceptable. We will ignore bale variability, concluding that variance will be above and below this limit, such that the overall average is 250 Kg/m^3.

Adjustments shall be made to the target density for moisture content, however. Referencing the Forest Product Laboratories’ Wood handbook, we know that the equilibrium moisture content of woody material is about 9% dry weight basis (dwb), at 50% relative humidity and 21℃ (Forest

Products Laboratory, 1999); which is approximately 9% wet weight basis (wwb). A bale may be stored for some period of time before shipment, allowing time for the material to dry. We want to maintain the ability to maximize truck shipping even when the material is dry. Therefore, the target density should be 250 Kg/m^3 (15.6 lb/ft^3) at 9% wwb moisture content. Typically green material is baled at a moisture content of 39% wwb. Adjusting the target density for "as baled" moisture content gives us a green bale target density of 373 Kg/m^3 (23.3 lb/ft^3). Assuming from previous calculations a 680 Kg (1,500 lb) maximum bale weight, we can confirm that 373 Kg/m^3 (23.3 lb/ft^3) x 1.56 m^3 (55 ft^3) = 581 Kg (1,281 lb) is less than the maximum; therefore a medium bale range is acceptable.

Optimizing Dimensions for Trucking

Bale dimensions must also be specified. First, nomenclature conventions: dimension D1 is perpendicular to the plane created by the tying material. Dimension D2 is perpendicular to D1 and parallel to the tying material. Dimension D3 is perpendicular to the plane created by D1 and D2. Bale compression is along the D3 axis. Tying material is parallel to D3. See Figure 1 for a pictorial representation of the described bale. We shall call all tying material wire, though it may consist of twine, wire, banding, etc.

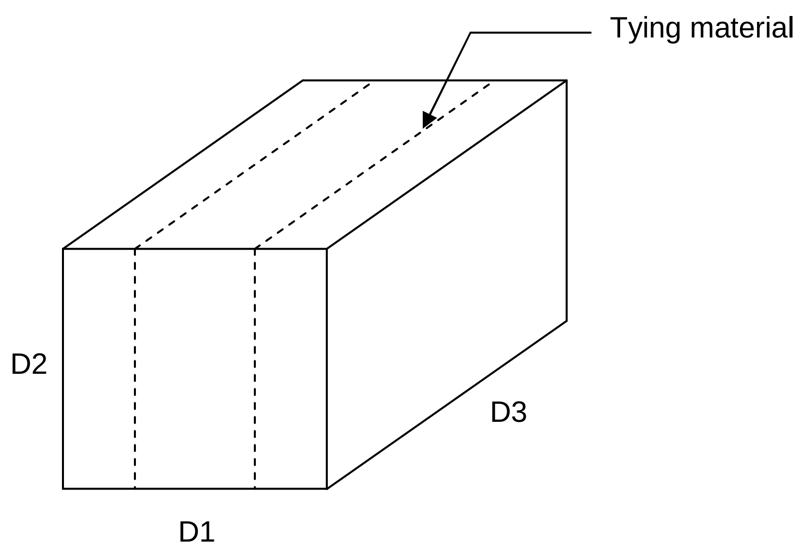

Figure 2. Bale dimensions identified for ease of describing constraints.

Using the information discussed earlier we can determine certain constraints:

- "Long" Material will be along the D1 axis, transecting the wire plane. This ensures that the material will be bound by the wire.
- D3 > 1.5 x D2. We have found that the compression axis length should be at least 1.5 times greater than the other wire axis. A smaller ratio tends to yield "egg" shaped bales rather than the target rectangular bales.

- D3 ≥ D1. A greater difference between the two dimensions uses less wire. The larger D1 is, the more wraps of wire are required. Extending D3 increases volume, while only incrementally increasing wire length.
- We assume that the D1 x D3 plane will be parallel to the transportation surface, thusly:
    - D1 should be a divisor of 2.4 m (8 ft) or 14.63 m (48 ft).
    - D3 should be a divisor of 2.4 m (8 ft) or 14.63 m (48 ft).
    - D2 should be a divisor of 2.4 m (8 ft).
- D1 should be as large as possible to minimize cutting material pieces.
- The bale must weigh less than 680 Kg (1500 lb).
- The volume shall be 0.85 – 1.56 m^3 (30 – 55 ft^3).
- Preference will be given to bale dimensions that have a D3/D1 ratio of 2, allowing interlocking stack possibilities.

Our data indicates that 58% of the material being baled has a lengthwise dimension larger than 1.2 m (46 in). Therefore D1 should be larger than 1.2 meters.

Using the above constraints, we determined the optimum bale size to be 1.22 m x 0.79 m x 1.58 m (4 ft x 2.6 ft x 5.2 ft). This bale has a volume of 1.53 m^3 (54 ft^3), a green mass of 571 Kg (1260 lb) and a dry mass of 383 Kg (844 lb).

Conclusion

From this discussion, we can surmise an appropriate target bale size and density for a baler intended to operate in the wildland urban intermix zone as part of forest health and fuels reduction projects. By using a bale size of 1.22 m x 0.79 m x 1.58 m with a green density of 373 Kg/m^3 and a equilibrium density of 250 Kg/m^3 we can maximize truckload potential while minimizing input energy. Furthermore, maximizing truckload potential increases the utilization opportunities for the biomass from residential scale fuels reduction projects.

Knowing the bale size, target density, and initial target density is only the first step in engineering an appropriate biomass baling system though. Further research needs to be conducted in order to determine both the energy required to reach the specified bale densities and the best method of handling over-length pieces.

Acknowledgments

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